I. Attachment Techniques for Heavy Truck Composite Chassis Members

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Contractors: Oak Ridge National Laboratory, Pacific Northwest National Laboratory
Contract Nos.: DE-AC05-00OR22725, DE-AC06-76RL01830

Objectives

- Overcome the technical issues associated with joining composite materials in heavy vehicles by developing technically robust and economically attractive joining techniques.
- Develop and validate one or more joint designs for a composite structural member attached to a metal member that satisfy the truck chassis structural requirements both economically and reliably.
- Solicit input from truck original equipment manufacturers (OEMs) and suppliers on the technical hurdles and needs associated with joining structural composite members in heavy vehicles. Use this information to guide the joint design and development activities.
- Publish information on the design, modeling, and testing methodologies that are developed to support the incorporation of composite materials into other chassis components.

Approach

- Collaborate with Delphi and its OEM partners to identify and address technical needs related to the manufacturing, joining, and implementation of a composite chassis component.
- Design attachment components and configurations in close coordination with the composite structural component development.
- Use modeling techniques to predict the performance of various joint designs, taking into account damage mechanisms and fatigue/life requirements.
- Characterize various composite materials and mechanical joint configurations through mechanical testing, considering variables such as hole size, hole fabrication method, bolt pre-load, inserts, combined loading, vibration, fatigue, and durability.
- Validate joint design for the composite structural member through track testing.

Accomplishments

- Conducted static and fatigue tests on a commercially available, component-independent, pultruded fiberglass composite material.
- Investigated several hole fabrication techniques, including water jet cutting, laser cutting, punching, drilling with a standard drill bit and Forstner bit, and drilling undersized holes and then reaming.
- Ran static and fatigue tests of composite specimens with holes fabricated by various methods to identify the method preferred for the least damage in the composite at an acceptable cost and complexity.
- Identified thermography as a reliable nondestructive technique for evaluating damage due to hole fabrication.
- Ran static and fatigue tests on Extren®/steel joints and baseline steel/steel joints (lap shear and cross tension).
- Conducted finite element analysis (FEA) modeling to optimize the geometry of a metallic insert for an all-carbon-composite component to address the bolt loosening due to creep in the composite member.
- Presented two papers at the 2004 SPE Automotive Composites Conference and Exposition in Detroit.

Future Direction

- Conduct bolt bearing and fatigue tests to investigate design modifications, such as inserts, molded-in holes, and 3-dimensional (3D) reinforcement to minimize the damage in the composite and improve the fatigue life of a composite-to-steel joint.
- Evaluate the impact of using adhesive bonding in place of and in combination with bolting, as well as the effects of environmental exposure and testing rate for the composite/steel Mode I and Mode II fatigue specimens.
- Use FEA modeling with input from the composite and joint tests to optimize and predict the performance of the composite/steel joint.
- Continue to work closely with the industrial team to develop the composite component and composite-to-steel joint design solutions to meet the demanding requirements of the heavy vehicle chassis environment.

Introduction

In May 2003, researchers at Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) began collaboration on a 4-year research effort focused on developing technically robust and economically attractive joining techniques to overcome the technical issues associated with joining lightweight materials in heavy vehicles. This work is being performed concurrently with an industry program led by Delphi to develop and commercialize composite chassis components, which will require resolution of the joining challenges. The industry project serves as a “focal project” that provides real load and service data to this project and will potentially field-test and implement the technology developed in this project. The initial focus of research is development and validation of one or more joint designs for a composite structural member attached to a metal member that satisfy truck chassis structural requirements both economically and reliably. Broadening the effort to include other structural joints, including composite-to-composite joints, is anticipated. Durability track testing of the first prototype composite component and joint is planned for the last half of 2005.

Component-Independent Material Evaluation

To gain an understanding of the performance of composite materials in a heavy vehicle structural chassis application, a commercially available pultruded fiberglass composite—Extren®, manufactured by Strongwell—was chosen for initial component-independent study. The pultruded composite consists of a continuous-strand mat with unidirectional rovings in the axial direction and a surface veil for corrosion and ultraviolet protection. The results will serve as a baseline for further testing of composites with 3D reinforcement and with low-cost, lightweight design modifications—such as modified washers, inserts, or adhesive bonding— to improve performance at the joint.

Hole Fabrication Techniques

The initial joint design for a composite component-to-steel member will likely include mechanical fasteners requiring holes in the composite member. The use of bolts through holes in the composite is a concern, especially because of the severe loading conditions and the long service life resulting in high cycle fatigue. Several hole fabrication techniques have been evaluated, including drilling with a Forstner bit, drilling with a standard tapered bit, laser cutting, water jet cutting, and punching. For each method, 12.7-mm-diam holes were machined in the center of 76.2 × 254 × 3.2 mm Extren® coupons.

Many of the water jet cut specimens had visible delaminations and cracks around the hole diameter. In some cases, the damage produced at the edge of the hole spread through the laminate thickness, puckering the coupon's surface layers around the hole at the back of the laminate during machining. Additionally, the cut was jagged instead of smooth and circular. This amount of damage was quite unexpected because of the prior success with the fiberglass composite for straight cuts. Two water jet cutting facilities, including one with significant experience with composite materials, attempted to machine the holes. In both cases, some of the specimens looked fairly good, but many had large areas of damage.

Although the laser-machined holes (conventional laser with 127–152 cm/min linear feed rate) had no visible damage, there was some residual carbon dust on the cut surfaces, as is normal in laser-machined polymers.

Open-hole tensile, static, and fatigue tests have been conducted on the specimens with holes fabricated with different methods. The results shown in Figure 1 indicate that the specimens drilled with the carbide-tipped Forstner bit have the highest average tensile strength with the least scatter in the data. As anticipated, the water-jet–cut specimens did not perform well because of the large amount of damage in many of the specimens. The results of the fatigue tests with R = 0.1 and a frequency of 5 Hz (Figure 2) at 70%, 50%, and 30% of ultimate stress do

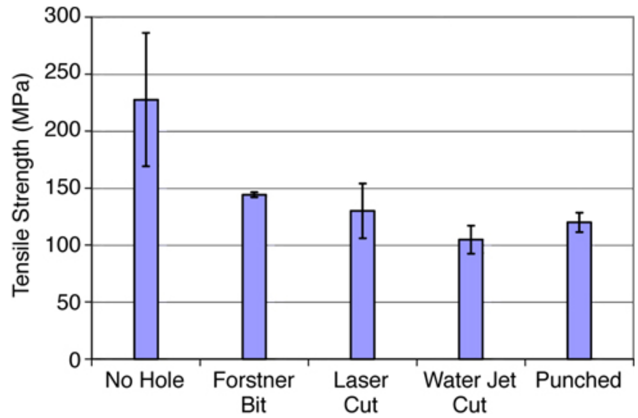

Figure 1. Comparison of ultimate tensile strengths for specimens with holes fabricated with different methods and the material with no hole.

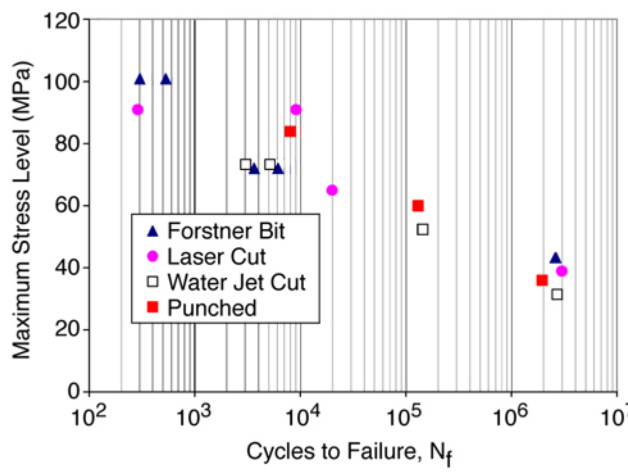

Figure 2. Fatigue testing results for specimens with holes fabricated with different methods.

not show a dramatic difference in fatigue performance between the specimens with different hole fabrication techniques. However, a difference will likely be detected at higher stress levels because of the variations in the static failure stresses. Additional tests are under way.

Specimens with a preferred hole fabrication method will be tested in bolt bearing and fatigue to evaluate design modifications, such as bolt pre-load, inserts, molded-in holes, and 3D reinforcement of the composite. The goal will be to minimize the damage in the composite and improve the fatigue performance of the resulting composite/metal joint.

Methods for Damage Detection

Several methods have been investigated for evaluating the damage associated with hole fabrication in the Extren® composite material, including dye penetrant analysis and flash thermography. The flash thermography method has good correlation with the X-ray dye-penetrant results.

Although the results from dye penetrant can be very good, the drawbacks include the time required for soaking, the contamination of the composite with the solution, and the requirement for an X-ray source. Additionally, for each material density and thickness, the time of exposure and power level must be optimized to get the desired results.

The flash thermography method was used to evaluate several of the water-jet–cut coupons. Thermography is a nondestructive technique that involves applying a heating (or cooling) stimulus to the surface of a test piece and imaging its thermal response with an infrared (IR) camera. In flash thermography, the thermal stimulus is in the form of a short-duration flash uniformly applied to one side of the part. The IR camera records the surface temperature of the opposite side of the part as a function of time. If sufficient temperature contrast can be obtained, changes in through-the-thickness diffusivity of the material can be measured.

Thermal diffusivity is the property governing the rate at which heat flows within a material; and any delaminations or cracks will affect the heat diffusion rate, thereby changing the surface thermal response. Therefore, by studying the time evolution of the surface temperature distribution, it is possible to obtain information on the depth, spatial extent, and thermal character of subsurface structures and defects.

The IR camera used in this study was a Raytheon Radiance-HS IR camera with a 50-mm lens, which operates in the 3–5 µm spectral range. With this camera, data are recorded as full field-of-view at a rate of 142 images/second and with a time resolution of 0.007 s. The flash system used was an Acute2 (2400 W·s) xenon flash lamp. The thermal images after flash were recorded for both sides of the coupons.

One advantage of flash thermography is that it can provide an indication of depth below surface that X-ray and visual examination cannot. The depth limit of flash thermography with this particular setup appeared to be about one-half of coupon thickness (1.5 mm). Possibilities to further enhance the thermal images and depth resolution of the flash thermography technique include the step-heat and lock-in techniques.

Additionally, because this is a nondestructive and noninvasive technique, flash thermography can be used during fatigue testing to monitor damage development and propagation in the composite material.

Extren® Static and Fatigue Testing

Baseline static and fatigue tensile testing was conducted for the pultruded fiberglass material. The fatigue tests were run with R = 0.1 at 70%, 50%, and 30% of ultimate stress at a frequency of 5 Hz (Figure 3). Although there was a fairly high level of scatter among the tensile specimens, the fatigue behavior was fairly consistent. Several of the specimens at 30% of ultimate stress reached runout with more than 1,000,000 cycles. As expected, the ultimate stress levels are significantly higher for the specimens with the loading axis in line with the axial reinforcing fibers.

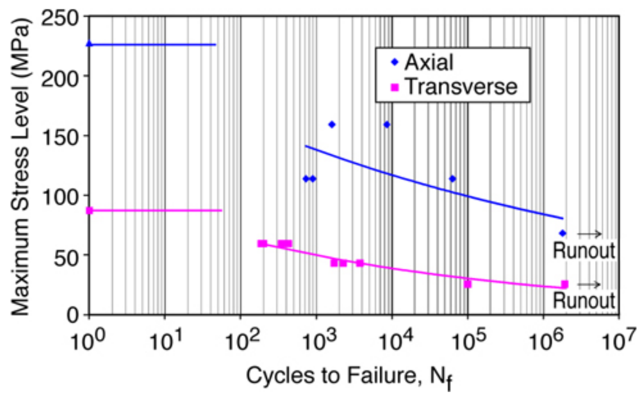

Figure 3. Tensile fatigue behavior of Extren® fiberglass composite.

To determine the feasibility of testing at a higher rate, the surface temperature of the composite specimens was monitored at both 5 and 20 Hz. Room temperature was approximately 23°C. At 70% of ultimate (between 300 and 1250 cycles to failure), the maximum temperature of the samples at 5 Hz was 27.5°, compared with 34.5°C for 20 Hz. This is the most severe loading case; but it has the shortest life, so the temperature does not reach equilibrium. For tests at 40% ultimate (40,000–45,000 cycles), the specimens at 5 Hz reached 27.6°, while the 20-Hz specimens reached 34.1°C. These temperature measurements are for the surface; the material is probably reaching a higher heat internally. In order to keep within the ASTM-recommended 10° temperature rise for these tests, the tests should be run slower than 20 Hz. However, the results indicate that a frequency greater than 5 Hz could possibly be used.

Bolt Torque and Pre-Load Investigation

A test methodology has been developed to study the effects of bolt torque levels on composite materials. Information derived from this work will ultimately be used to support the characterization of bolted composite assemblies tested as part of this program, as well as provide insight into the design and manufacture of a composite truck chassis.

When a composite assembly is bolted together, the tightened bolts and other hardware (e.g., washers, nuts) apply an external compressive stress to the composite through the thickness. This bolt pre-load may be beneficial or detrimental to the composite, depending on the amount of applied pressure. Snug bolts can minimize slippage or movement of the bolt shank in the composite hole, thereby reducing the possibility of wear and abrasion at the edge of the hole. The additional compressive force may also help “clamp” the individual composite layers together, resisting delamination propagation when other external forces are applied to the assembly. Alternatively, too high a pre-load could cause the clamping force to exceed the transverse compressive strength of the composite, essentially crushing the material or forcing penetration of the bolt hardware into the composite surface.

Figure 4 is a schematic of the basic test setup used to characterize the effects of bolt pre-load on test specimens. An Interface washer load cell, model LW2050, was positioned between the composite laminate backed by a hardened flat steel backing plate, and a second backing plate. Applying a torque to the bolt applies a compressive force to the assembly, which is in turn measured by the washer load cell.

For a given material and thickness, the washer load cell setup has proved useful to study the effects of a number of factors on joint design, including (1) composite pre-load as a function of bolt torque, (2) the effects of multiple bolt tightening/loosening cycles, (3) specimen-to-specimen variability, (4) the effects of re-tightening bolts, and (5) the loss of bolt pre-load with time.

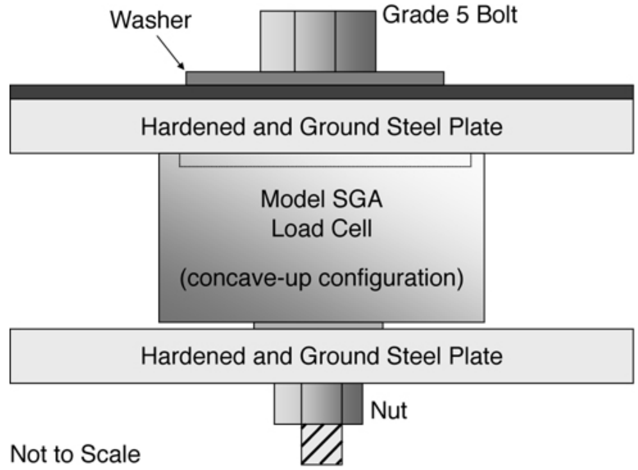

Figure 4. Bolt pre-load test schematic.

Hardened flat steel plates are required on both sides of the washer load cell to ensure that the load is aligned correctly on the load cell. The use of this stack-up in bolted assemblies for static and fatigue testing may be impractical. Strain-gaged bolt load cells are under evaluation for use as an alternative to the washer load cells to monitor the bolt load during mechanical testing.

Figure 5 shows the loss of pre-load as a function of time for various test materials that have been bolted together with a 67.8 N-m (50 ft-lb) applied torque. The loss of pre-load with time is relatively low for a steel-to-steel bolted assembly and increases for the composite assemblies. The greatest loss of pre-load occurs with the thick composite substrate (6.35 mm). This likely results from the increase in the thickness of the glass fiber mat in the thicker composite.

A significant part of the loss of pre-load for these samples occurs during the first 5 minutes after the bolt has been tightened. A very rapid decrease in pre-load occurs within the first 30 seconds after application of the torque. Initial test results suggest that retightening the bolts within a few minutes of the initial assembly may help reduce the bolt’s pre-load loss rate with time, and the overall loss of pre-load.

To determine the effects of the level of bolt pre-loading on the mechanical properties of the composite materials, bearing tensile and fatigue tests will be

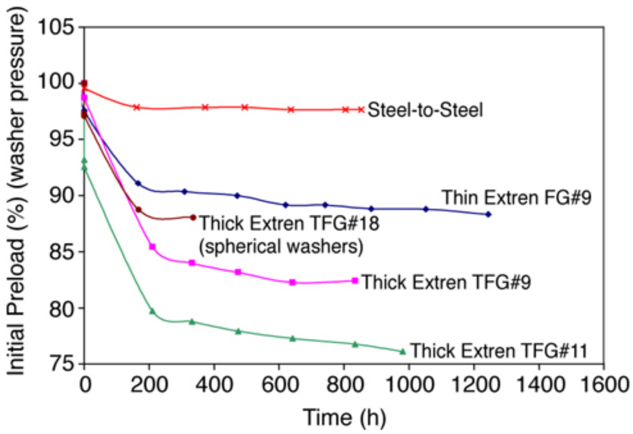

Figure 5. Loss of pre-load for various bolted assemblies.

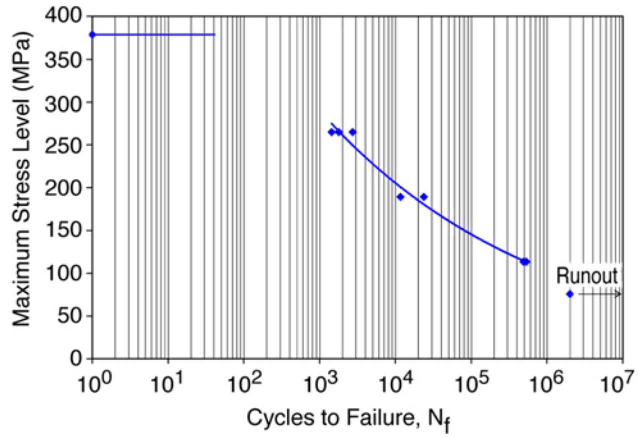

Figure 6. Tensile fatigue behavior of 3D reinforced glass/polymer composite.

conducted on the pultruded fiberglass composites. Varying levels of torque on the bolts, as well as Huck bolts, will be evaluated. It is anticipated that the Huck bolts will yield a more consistent pre-load level.

Evaluation of 3D Reinforced Composite

Static tensile and fatigue tests have been conducted on 3D glass-reinforced composites to determine the effects of the 3D reinforcement and to evaluate their feasibility for use in the structural chassis component. The initial composites tested had both high levels of voids and a clay filler material that contributed to a decrease in static strength and poor fatigue performance. Once the processing was improved to eliminate the clay filler and reduce the void content, the static tension and fatigue properties improved significantly. Several material systems are under evaluation, and the fatigue curve for one of the 3D glass-reinforced polymers is shown in Figure 6.

Additionally, hole fabrication techniques were compared for the 3D reinforced material to ensure that the results seen in the pultruded polymer composite (with significant chopped glass mat) would translate for a highly oriented composite. For the Extren® material, the water jet cut specimens showed the most damage. However, the delamination occurring in the 3D reinforced material was limited to the midplane of the composite and did not appear at the surface. Again, the specimens cut with the carbide-tipped Forstner bit had the least visible damage.

Steel-to-Steel Joint Evaluation

To establish design targets of an existing chassis joint, 6.35-mm-thick grade 6 steel plates were joined by a Huck bolt to achieve two testing configurations commonly used in joint performance evaluations, lap shear and cross tension. This baseline will be used to design and optimize the composite/steel joint. Static and fatigue tests were conducted to characterize the performance of the joints. In the static tests, a bearing failure mode (composite material shear-out) was observed for the lap shear specimens, whereas bolt failure (stripping of the nut collar) occurred in the cross tension specimens. The failure load for the lap shear specimens were approximately 128 kN, while the cross tension specimens failed at approximately 175 kN.

Cyclic fatigue tests were also performed on the joints under a tension–tension ratio of R = 0.1 for both lap shear and cross tension configurations. Figure 7 illustrates the fatigue strength of the lap shear and cross tension specimens for all completed tests. Unlike for the static tests, the fatigue failure for the cross tension fatigue tests initiated from the steel/steel contact periphery on the faying interface where the structural stress is maximum. Additional tests are ongoing.

Extren®/Steel Joint Evaluation

Preliminary composite/steel joints (both lap shear and cross tension coupons) were assembled and tested to understand the fatigue behavior and failure mechanisms associated with joining the fi-

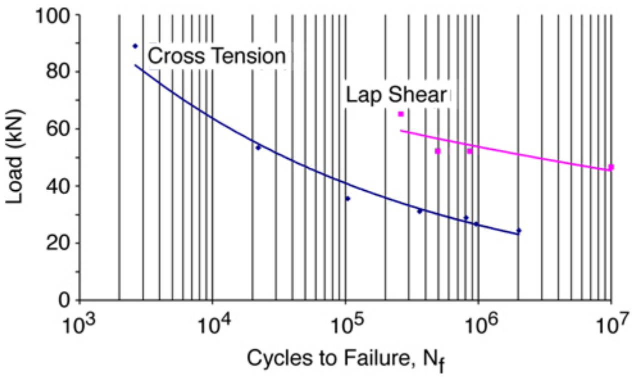

Figure 7. Fatigue test results of the lap shear and cross tension steel assemblies joined by a Huck bolt.

berglass composite to steel with a bolt. Joints were assembled using 3.2-mm-thick composite with 1.4-mm-thick 1008 steel. All composite/steel joints were joined with 6.35-mm grade 5 bolts, torqued to 13.6 N-m (10 ft-lb).

The following joining and testing parameters for joint strength are under investigation:

- Effect of washer size
- Effect of fatigue test frequency and temperature rise
- Effect of structural adhesive
- Effect of environmental exposure

Washer Size Effects

Figure 8 illustrates the static strength comparison among lap shear samples with a nominal size washer (15.9 mm diam), an oversize washer (25.4 mm diam), and a steel plate washer (50 × 35 × 6 mm). Under lap shear loading, the static strength increases approximately 10% with an oversize washer and approximately 20% with a plate, compared with the nominal washer. The samples with nominal and large washers show the typical characteristics of a bearing type of failure, but the samples with the constraining plate do not show a clear load drop prior to the peak strength. A similar cleavage tension failure mode was observed in all three washer types, and the damage initiated from the periphery of the bolt hole.

Figure 9 illustrates the fatigue strength comparison of lap shear and cross tension samples with the

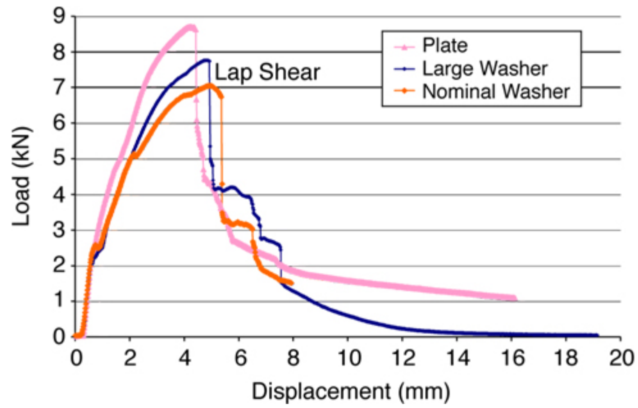

Figure 8. Static strength comparison of washer size effect.

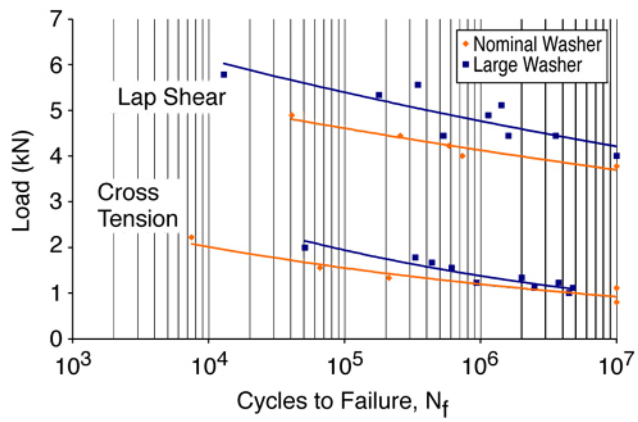

Figure 9. Fatigue strength comparison of washer size effect.

nominal and oversize washer. On average, joints with larger washers yield higher fatigue strength than joints with nominal washers. This effect is more prominent under lap shear loading than under cross tension loading conditions. Under fatigue loading, damage on the composite plates initiated right underneath the periphery of the washer for both loading cases.

Frequency Effects

Fatigue tests are normally carried out at the highest frequency possible in order to minimize test duration. Typically, the maximum temperature rise allowed in the test material should be less than 10°C during fatigue testing. To study the effects of frequency on the composite/steel joint, lap shear fatigue tests were conducted at 5, 15, and 20 Hz with R = 0.1. The coupon temperature was monitored with thermocouples, and the maximum temperature rise for each frequency was recorded. At a frequency of 15 Hz, the maximum temperature rise was 5°C; at 20 Hz it was 9°C, which is just below the threshold value. Because of the degree of scatter in the material properties of this material, no significant change in the fatigue life at each fatigue level was apparent. Based on these results, a maximum test frequency of 15 Hz was chosen for the composite/steel joints to avoid inducing significant temperature changes in the sample during fatigue testing.

2D vs 3D Polymer Composites

Lap shear coupons were assembled with a 3D reinforced glass composite to investigate the fatigue behavior and failure mechanisms associated with joining the composite to steel with a bolt. The joint static and fatigue performance was then compared with the performance of the pultruded composite/steel joints.

The 2.54-mm-thick composites were joined to steel in the same manner as the Extren®/steel bolted joints with a 25.4-mm washer. The static strength of the 3D composite is approximately 3 times greater than that of the 2D Extren® composite. However, hybrid joints assembled from each composite substrate with steel yielded comparable static strengths (Figure 10). A cleavage tension failure was observed in joints assembled with Extren®, and a shear-out failure mode was observed in joints assembled with the 3D composite.

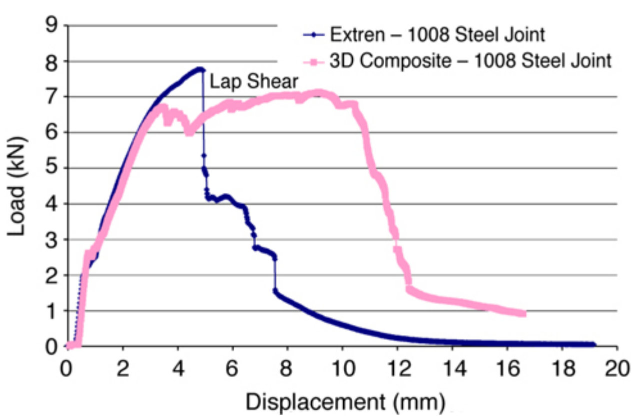

Figure 10. Static joint strength comparisons of composite/steel joints.

The fatigue strength of the hybrid joints assembled with the 3D composite was also comparable to that of the 2D composite. Figure 11 is an illustration of the fatigue strength comparison in terms of percentage of peak load. These testing results indicate that the fatigue strength of this type of hybrid joint is more sensitive to the geometry of the joint design than to the material substrate.

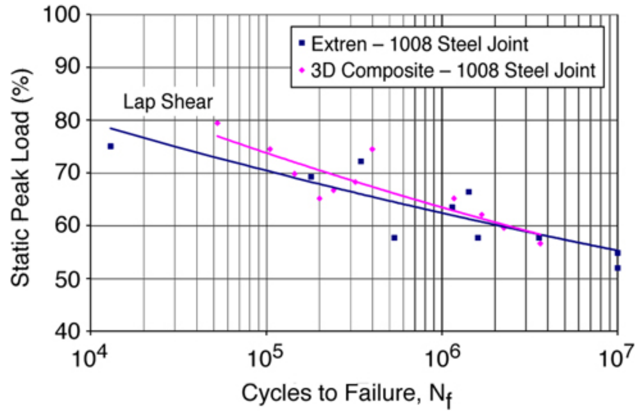

Figure 11. Fatigue joint strength comparisons of composite/steel joints.

Modeling

Genoa Evaluation

The joining team has investigated the commercial software GENOA to evaluate the feasibility of using it to predict the static and fatigue strength of composite/steel joints. Three staff members from ORNL and PNNL attended the GEONA training classes.

GENOA is an integrated structural analysis and design software that originated in the aerospace composite community. Its progressive failure analysis module predicts crack initiation, growth, and final failure for monolithic and 2D/3D braided, laminated, stitched, and woven composite materials based on the unit cell formulation originated by the National Aeronautics and Space Administration. The initiation and damage growth can be due to static, fatigue, thermal, and impact loading; and it is identified by the industrial team as the candidate software to be used in their project.

The feedback on the software from the staff members that attended the training classes was mostly positive. GENOA couples analyses on different scales and provides progressive failure analysis capabilities that are specifically tailored for composites. However, the current version has the following limitations that may hamper its use for the joint analysis:

- GENOA does not support more than one element type. Therefore, modeling of the joint area would have to be performed using solid elements.

- GENOA does not have contact modeling capability. Therefore, the interaction between the fastener and the plate materials, critical for predicting the fatigue life of the joint, cannot be modeled with this contact included.
- GENOA has demonstrated its ability to predict failures of composite samples with continuous fibers. Its capability to predict progressive damage for composites with randomly distributed chopped fibers needs to be further evaluated and established.

Joint Modeling

ABAQUS was used to analyze the effect of washer size in a bolted joint consisting of pultruded fiberglass composite and steel. The solid models were linear elastic, and the pre-load was produced by turning the nut by 90°, simulating a torque of 13.6 N-m (10 ft-lb). A small washer resulted in 20% more compressive strain in the composite than in the large washer. This prediction was validated through the joint mechanical testing results showing an improved static strength and fatigue resistance for a larger washer.

For an all–carbon reinforced composite component bolted to a steel component (design provided by the industrial team), three insert geometries were evaluated under two loading conditions. The metal inserts were selected so that the compressive load caused by the bolt tightening is fully carried by the metal insert, and the load is transferred to the composite through the bond between the insert and the composite. This will mitigate the issues associated with bolt loosening due to creep and/or damage in the composite during bolt installation.

The three insert designs include a cylindrical steel insert, a tapered insert with the large diameter at the bolt head side of the composite, and a tapered insert with the large diameter on the steel side of the composite. One assembly is shown in Figure 12. The model was evaluated under two loading conditions: a bending force and a lap shear force. The measure of performance to compare the different insert geometries was a component of traction nor-

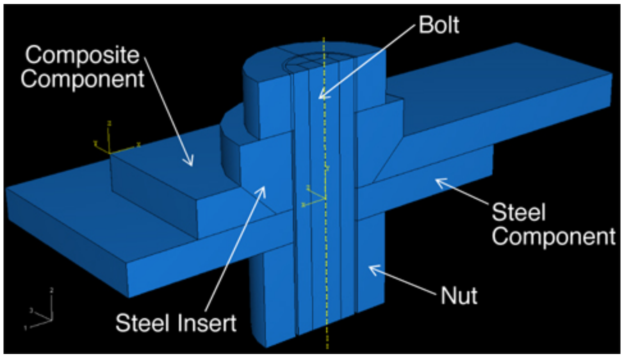

Figure 12. Finite element model of composite/steel bolted joint with tapered insert.

mal to the composite/insert interface that would produce a peeling stress in the adhesive. Because actual loads are not yet available for the actual chassis component, failure stresses from the steel/steel joint testing for lap shear and cross tension (bending) were used with the model. This is a worst-case load application and is unrealistic because the pre-load in the bolt is overcome, and contact between the steel and the composite are lost.

Qualitatively, the results match the results obtained for lower load levels: the tapered insert with the large diameter at the bolt head side of the composite exhibits the best performance. The model of the joint and insert will be added to the system model for additional investigation. As design and material changes are made and the loading cases are refined, further optimization of the joint, including inserts, will be possible.

Fatigue

Components in a truck chassis undergo complex random variable fatigue loading during their lifetime. The loading spectrum can be estimated from measurement results acquired in field tests or test-track runs, where a component is instrumented with accelerometers, strain-gages, and linear variable differential transformers. A majority of the cycles reach low load levels and are generally of concern only if their frequency approaches a resonant frequency of the structure. Resonance issues can be eliminated by adequate design of a component. Higher loads commonly take place at lower frequencies. Repetitive loads below the static limit can initiate damage, especially in the vicinity of stress raisers such as bolt holes and contacts. Therefore, the prediction of low-frequency fatigue life is of prime interest for chassis structural application.

Cumulative damage caused by low-frequency cycles is estimated using certain damage laws in conjunction with the results of constant amplitude fatigue tests. One of the most common damage laws is the Palmgren-Miner linear relationship. This law assumes that fatigue cycles at a specific load level always result in the same damage regardless of the loading history. The Palmgren-Miner model yields acceptable results for metals and is almost exclusively used for life predictions in practical applications. A literature review has revealed that this relationship may grossly overestimate or underestimate the fatigue life of composites. Because of this, empirical and semi-empirical non-linear damage laws have been developed for a variety of composites. In addition, Goodman diagrams can be used to account for varying R ratios of constant amplitude fatigue tests that are used as a basis for fatigue life predictions. All these methods require significant testing.

It will be necessary to evaluate the applicability of Palmgren-Miner's law for selected materials as part of this project in order to predict long-term fatigue performance. If this law does not reasonably represent actual material behavior, then an appropriate nonlinear relationship must be determined through additional testing, or the uncertainty must be taken into account by using appropriate safety coefficients during design. Although GENOA has shown promise for predicting the fatigue performance of the 3D reinforced composite material at constant stress levels, the software uses Miner's rule for variable stress levels.

Presentations

L. Klett, B. Frame, and V. Kunc, "Damage at Holes in Bolted Composite/Steel Joints for Heavy Vehicle Chassis Components," presented at the 2004 SPE Automotive Composites Conference and Exposition, Detroit, September 14–15, 2004.

X. Sun, D. Herling, and E. Stephens, "Static and Fatigue Strength Evaluations for Bolted Composite/Steel Joints for Heavy Vehicle Chassis Components," presented at the 2004 SPE Automotive Composites Conference and Exposition, Detroit, September 14–15, 2004 .

Acknowledgements

The principal investigators would like to acknowledge the valuable contributions of other members of the research team, including Barbara Frame and Vlasta Kunc at ORNL and Xin Sun and Elizabeth Stephens at PNNL.